New Modeling & Evaluation Approach for Capacitive Occupant Detection in Vehicles

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ABSTRACT
Capacitive occupant detection is a contactless sensing technique which helps to improve safety standards in vehicles. This paper details the problem of relating measured sensor signals with physical model parameters. An innovative modeling approach is discussed, which takes into account different current pathways including also the influence of human passengers. Furthermore, a new electrode area variation method is introduced which allows to extract wanted model parameters. Finite Element Simulation shows that the proposed electrode area variation method is applicable for capacitive occupant detection sensors.

1. INTRODUCTION
To improve automotive safety standards contactless sensing methods are needed. With the help of capacitive sensing methods the presence, sort and position of an object or person can be detected [1] [2]. This information about the occupancy status can be used for triggering safety devices, such as air bag or restraint systems only in the case when the seat is occupied. The working principle of capacitive detectors is depicted in Figure 1. Different current pathways contribute to the measured sensor signal. In the case of a transmitter and receiver electrode, these pathways need to be modeled with the help of an electrical two port network. The lumped two port parameters depend on electrode geometry, electrode placement, environmental variables, object geometry and object related electrical properties. The values of these network parameters need to be extracted in order to serve as input for a decision algorithm which determines the occupancy status of the seat.

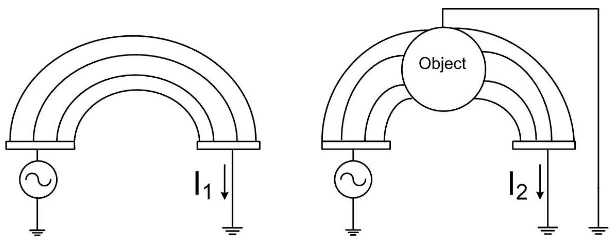

Figure 1: Perturbation of the electric field caused by an object results in a difference of measured sensor signals.

In the next sections different models for the seat detection problem in vehicles are introduced and discussed. The main focus of this paper is the introduction of an electrode area variation method. This method must be used to retrieve a complete set of physical model parameters, which is not the case for other reported solutions [6] [3]. The application of the electrode area variation principle allows to set up an improved occupancy detection system.

2. MODELING APPROACH
The sensing situation in the case of a receiver and a transmitter electrode placed on a vehicle seat is given in Figure 2.

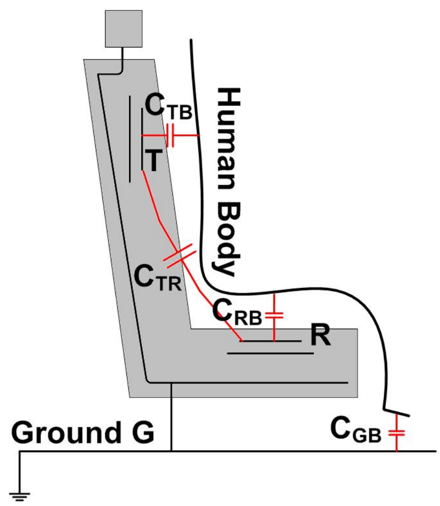

Figure 2: T represents a transmitter and R a receiver electrode placed on a vehicle seat. Possible current pathways are modeled by the physical parameters C_{TR},C_{TB}, C_{RB} and C_{GB}

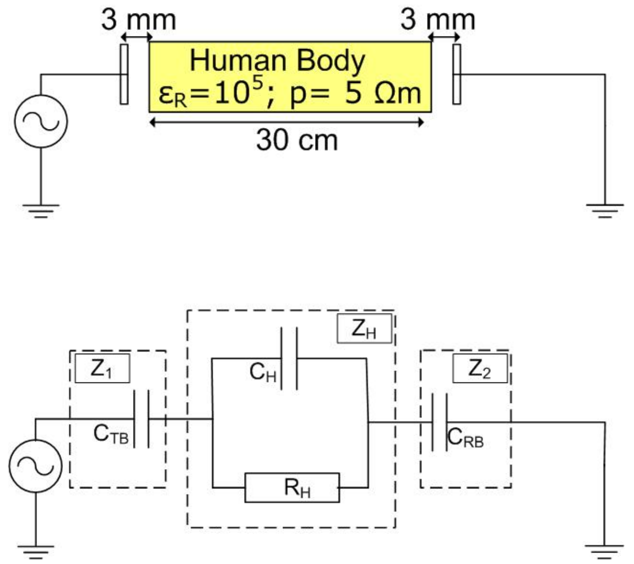

Figure 3: Equivalent electrical circuit modeling the current pathway over the human passenger.

The direct coupling of sensing electrodes to ground is reduced by screening electrodes. Possible current pathways are the direct coupling between the electrodes given by C_{TR} or the coupling via the human body which depends on C_{RB} and C_{TB}. In addition the current can be shunted away from the receiver by human body to ground coupling C_{GB} [3].

2.1 Human Body Modeling

To model the interaction of electrical fields with human tissues is a very challenging task and depends strongly on the frequency range of interest [11]. In this paper sensor signals with a frequency of 10 kHz are modeled. For an electrical field which is varying with 10 kHz the human body can be characterized by a specific resistance of $\rho = 5\ \Omega$m and a relative permittivity of $\epsilon_R = 10^5$ [11]. An equivalent electrical circuit for the human body is given by a parallel RC element [10]. In order to figure out contributions of the human body to the sensor signal, the impedance Z_H of the human parallel RC element must be compared to the coupling impedances Z_1 and Z_2, see Figure 3.

$$Z_H = \frac{R_H}{1 + j\omega C_H R_H} \tag{1}$$

$$Z_1 = \frac{1}{j\omega C_{TB}}$$

$$Z_2 = \frac{1}{j\omega C_{RB}}$$

For a typical sensing situation on vehicle seats the geometry of the human body can be approximated by a cuboid with a base area of 10 cm^2 and length of 30 cm, see Figure 3. The resistance and capacitance coefficients in the model are calculated using the following equations [4].

$$C = \epsilon_0 \epsilon_R \frac{A}{d} \tag{2}$$

$$R = \rho \frac{L}{A}$$

A summary of the resulting model parameters is given in Table 1. The modeled current pathway through the human

Table 1: Human model parameters

Frequency [kHz]	10
Electrode Area	10 cm^2
Distance to passenger	d=3 mm
Human cuboid length	l= 30 cm
Human cuboid base area	10 cm^2
C_{TB} [pF] = C_{RB} [pF]	2,9
C_H [pF]	2933
R_H [kΩ]	1,5
$\|Z_1\| = \|Z_2\|$ [MΩ]	5,5
$\|Z_H\|$ [kΩ]	1,45

passenger is dominated by coupling impedances Z_1 and Z_2. For 10 kHz signals these coupling impedances are more than thousand times higher than human impedance. Emphasizing this fact, the human body is modeled by a simple node in the network, which means the impedance of the passenger is neglected in the observed frequency range. The modeling situation is changing for higher frequencies because the electrode to body coupling impedances are decreasing with increasing frequency. In the MHz range sensor models have to consider human impedances too, which increases the complexity of the model.

2.2 Sensor model

Four capacitances are contributing to the measured sensor signal, see Figure 2. These capacitances are forming a bridged T-network. According to the previous mentioned facts and approximations the human passenger is represented by one node in the network. For an arbitrary sensing situa-

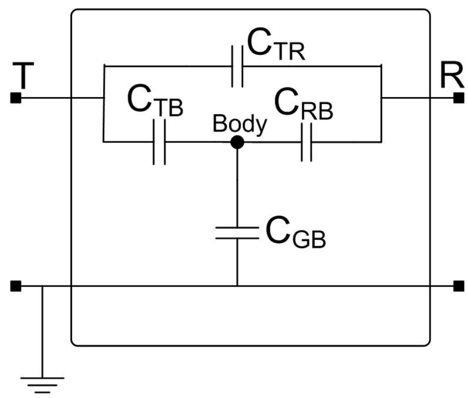

Figure 4: Two port network modeling an arbitrary sensing situation on a vehicle seat for a 10 kHz sensor signal.

tion on a vehicle seat the model given in Figure 4 depends on four parameters which are used for determination of the occupancy status. A seated child in an infant seat for example results in coupling capacitances C_{RB} and C_{TB} which are ten times smaller than in the case of a seated adult [6].

3. ELECTRODE VARIATION PRINCIPLE

Extraction of the sensor model parameters C_{TB}, C_{RB}, C_{GB} and C_{TR} is not possible for the case of one two port network

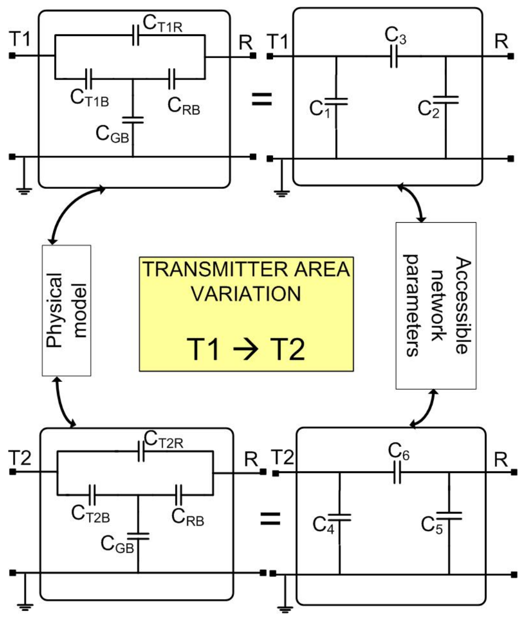

Figure 5: Electrode area variation method. Electrode variation on the transmitter side creates a second network with two additional model parameters, namely $\mathbf{C_{T2B}}$ and $\mathbf{C_{T2R}}$.

consisting of four unknown capacitances because every linear and passive two port network is characterized by only three independent parameters [9]. Our new approach to evaluate sensor model parameters is based on the fact that if one cannot fix one of the four parameters one is at least able to change some sensor model parameters in a defined way. The change of the sensor model parameters is done by an electrode area variation at one side of the sensor network. In the case of a transmitter electrode variation we assume that the receiver to body C_{RB} and body to ground C_{MB} coupling is not influenced by this operation. This procedure results in two networks with six unknown sensor model parameters, see Figure 5. The relationship between sensor model parameters and measured two port parameters is given by Equation 3.

$$\frac{1}{C_{T1B}} = \frac{C_2}{C_1}\left[\frac{C_1 + C_2 - C_4 - C_5}{C_1C_5 - C_2C_4}\right] \quad (3)$$

$$\frac{1}{C_{RB}} = \frac{C_1 - C_4 + C_2 - C_5}{C_5C_1 - C_4C_2}$$

$$\frac{1}{C_{GB}} = \frac{1}{C_1 + C_2}\frac{C_B}{(C_5C_1 - C_4C_2)}$$

$$\frac{1}{C_{T1R}} = \frac{(C_1 + C_2)^2 - (C_1 + C_2)(C_5 + C_4)}{C_3C_A - C_1C_B}$$

$$\frac{1}{C_{T2B}} = \frac{C_5(C_1 - C_4 + C_2 + C_5)}{C_4(C_5C_1 - C_4C_2)}$$

$$\frac{1}{C_{T2R}} = \frac{(C_1 + C_2)^2 - (C_1 + C_2)(C_5 + C_4)}{C_6C_A - C_4C_B}$$

With

$$C_A = (C_1 + C_2)^2 - (C_1 + C_2)(C_5 + C_4)$$

and

$$C_B = C_1C_5 + C_5C_2 - C_1C_2 - C_2C_2$$

As already mentioned in the case of a transmitter variation the assumption of an unperturbed receiver electrode must hold in order to make the previous described procedure applicable. In order to show that this assumption is true for the seat detection case, the effect of a transmitter area variation is simulated in the next section.

4. SIMULATION EXAMPLE

To calculate the corresponding physical model parameters the finite element method (FEM) is used. A test element in form of a cylinder is placed on a seat, see Figure 6. Transmitter and receiver electrodes are covered by seat material. The seat environment is filled with air and natural boundary conditions for the electrical potential are assumed. A summary of important geometry and material parameter is given in Table 2.

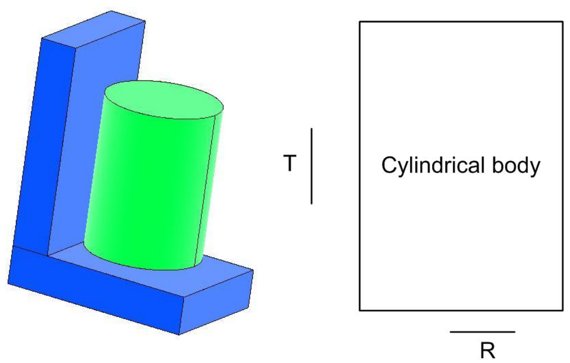

Figure 6: FEM model of a cylindrical test body placed on a seat. The transmitter and receiver electrodes are placed at the bottom and the backside of the seat.

Table 2: FEM simulation data

Electrode Area T1	2400 cm^2
Electrode Area T2	1200 cm^2
Electrode Area R	2400 cm^2
Electrical permittivity of the seat	3
Base area of the cylindrical body [cm^2]	2827 cm^2
Hight of the cylindrical body [cm]	80

Table 3: FEM simulation results

Model parameter	Step 1 (T1)	Step 2 (T2)	$\frac{\text{Step 2}}{\text{Step 1}}$
C_{TB} [pF]	11,2	8,1	0,723
C_{RB} [pF]	13,8	13,9	1,007
C_{TR} [pF]	0,3	0,2	0,667
C_{GB} [pF]	62,5	63,5	1,016

In accordance with the already described electrode area variation method two simulation steps are performed and the physical model capacitances are calculated for the case of two different transmitter electrode areas, namely T1 and

T2. The simulation results are presented in Table 3. The conclusion from this simulation example is that the relative change in the capacitances C_{RB} and C_{GB} is negligible in comparison to the relative change in C_{TB} and C_{TR}. The basic assumption for the electrode area variation method of an unperturbed receiver to body and body to ground coupling is fulfilled for typical occupancy sensing environments in vehicles.

5. CONCLUSION & OUTLOOK

We introduced a physical sensor model for capacitive occupant detection in vehicles including human passengers. The demonstrated electrode area variation method allows to extract a full set of physical model parameters. In comparison with other patented solutions [5] [7] the reported method allows to distinguish between different grounding behavior of passengers and therefore the sensitivity of capacitive occupant detection sensors is increased. Further investigations will focus on the MHz frequency range. In this frequency range the human body modeling approach is more complicated because human impedances are no longer negligible. In addition we will investigate the sensor performance in a certain frequency range and propose a new sensor model. For this purpose similar measurement techniques like presented in [8] will be used.

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6. REFERENCES

[1] L. K. Baxter. *Capacitive Sensors - Design and Applications.* IEEE Press Series on Electronics Technology, 445 Hoes Lane; Piscataway, NJ 08855-1331 USA, 1997.

[2] N. Gershenfeld. Non-contact sensing of people and things. In *Occupant Detection and Sensing for Smarter Air Bag Systems*, pages 85–89. SAE, 2004.

[3] K. Jinno, M. Ofuji, T. Saito, and S. Sekido. Occupant sensing utilizing perturbation of electric fields. In *Occupant Detection and Sensing for Smarter Air Bag Systems*, pages 167–180. SAE, 2004.

[4] A. Kip. *Fundamentals of Electricity and Magnetism.* McGraw-Hill Book Company, INC., New York, 1962.

[5] Y. Lu, L. Eisenmann, C. Marschner, and R. Griessbach. *Patent No.: DE 19812626 A1.* Bayerische Motorenwerke AG, 80809 München, 1999.

[6] C. Marschner. *Messverfahren zur Eliminierung von Erdungseinflüssen bei kapazitiven Detektoren und ihre Anwendung zur Sitzbelegungserkennung in Kraftfahrzeugen.* Technische Universität München, Arcisstrasse 21; 80333 München; Germany, 2004.

[7] C. Marschner, R. Griessbach, L. Eisenmannand, and Y. Lu. *Patent No.: DE 19847750 A1.* Bayerische Motorenwerke AG, 80809 München, 1998.

[8] P. Pring and M. Smith. A wideband spectrometer for the measurement of permittivity. *Conference on Dielectric Materials, Measurements and Applications*, pages 326–327, June 1988.

[9] H. Rühl. *Zweipole und Vierpole in elektronischen Schaltungen.* UTB Hüthig, 1975.

[10] J. R. Smith. Field mice: Extracting hand geometry from electric field measurements. *IBM Systems journal*, 35(3 4):587–608, 1996.

[11] A. V. Vorst, A. Rosen, and Y. Kotsuka. *RF/Microwave Interaction with Biological Tissues.* John Wiley & Sons, Inc., Publication, Hoboken, New Jersey, 2006.